LAND DEGRADATION AS A COMPLEX STABILITY PROBLEM

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ABSTRACT

This paper reviews recent work in the fields of ecology and economic ecology that contribute to a better understanding of the grazing and erosion debate. The approach is through dynamical systems models represented by differential equations and expressed by the phase-space diagrams for systems. The trophic web concept constrained by competitive and societal objective functions is found to be suitable to free-range grazing in environments that are spatially variable in their productivity. New models are needed for the case of grazing managed by shepherds.

Key Words: Dynamical systems, trophic web, economic ecology, grazing, erosion

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INTRODUCTION

Although 'overgrazing' is widely cited as the major cause of catastrophic erosion, leading to drastic actions to constrain the grazing densities, this century-old hypothesis has been seriously questioned (Scones, 1996).

In 1987 a project was started to investigate the interactions of erosion and grazing, through a better understanding and modelling of the processes involved. Three major developments in the last two decades have brought this project much closer to the original goals. In ecology, the modelling of trophic web (food-chain dynamics) has moved swiftly ahead. In hydrology, the interaction of vegetation and water balance has adopted a new and more helpful paradigm (Eagleson, 1979). In resource economics the development of exploitation ecosystems theory (Rosenzweig, 1977) and the development of the ecological economics approach (Regev et al., 1998) have opened new frontiers.

Land degradation is the reduction and loss of the biological or economic productivity caused by land-use change, a physical process or a combination of the two. These include processes arising from human activities and habitation patterns, such as soil erosion, deterioration of the physical, chemical and biological or economic properties of the soil, and long-term loss of vegetation.

This review paper seeks to provide an assessment of the progress towards a general approach to land degradation. Based on recently published research, it can be applied to the wide range of bio-physical and economic conditions that are found in the geographical mosaics that form the surface of the earth, mainly through the interactions of erosion and vegetation. This interaction was studied by the author) as the competition between vegetation and erosion for water using the classic Lotka-Volterra model, in which the growth rate of two populations in competition for a resource are expressed by differential equations (Thornes, 1987). May had already expanded the methodology to include difference equations and analysed the dynamical behaviour of single species. He showed its use in single species ecological systems to establish stability of the system when subjected to various perturbations (May, 1976). This procedure is exemplified in the methodology section of this paper.

As the concept of the trophic web developed in the middle of last century, a strong case was made for the predominance of a tightly coupled hierarchical arrangement of the flow of food and energy through an ecosystem. Ecological studies proposed that this layered structure reflected the available resources. Although there is some evidence that the number of levels generally increases with environmental productivity in space and time (Hairston et al., 1960), it is now generally argued that a three-layered hierarchy is prevalent (Fretwell, 1987). Oksanen (1990) has used the dynamical systems methodology to examine the proposition that the population at a particular level in the trophic web depends on interaction with the levels above and below, as well as spatial competition between the same species (horizontally in the web) for a resource. He also considered the effects of in-homogeneities in space on the interactions (resource rich and poor regions).

These trophic web issues are considered in the 'real space' of the paper. There is a time element here. The system evolves over the centuries, producing the bio-geographies of today. In the historic time scale also, as the environmental perturbations (such as climatic variations) occur, the behaviour of the system also changes and characteristically the complex produces a switching in the relative abundance of one level against another, leading to an unstable cycle of 'boom and bust' conditions (Thornes and Brandt, 1994). Using the dynamical systems analysis methodology, the problem of sustainability is involved as the resource-base is utilised. These circumstances particularly apply to the conditions in which the top-most predators are humans whose harvesting is governed more by economic behaviour (maximisation of personal gain) than by considerations of self-survival by the harvesting species (Darwinian). Regev et al. (1998) have modelled the three-level trophic web and have developed ecological models strongly constrained by economic parameters.

In the soil conservation school, it is a widely-adopted belief that the grazing of vegetation by domestic animals (goats, sheep, camels) is the almost universal cause of land degradation. There are strong reasons for this belief. The first is the experimental and field verified 'law' that erosion increases as the vegetation canopy cover percentage falls and that this is the most dramatic below 30% cover (Elwell and Stocking, 1976: Francis and Thornes, 1990). Secondly, it is widely observed that soils surfaces and internal profiles are materially transformed by the compaction induced by cattle trampling. Third, in under-developed areas over-stocking arises from social and economic constraints on farming activities. As a result, colonial agricultural advisors blamed native herders for the severe erosion that accompanied early settlers in Africa and Australasia. Sometimes the lack of careful historical research led to the failure to recognise the true causes of erosion and the evidence was not consistent with the hypothesis (Rowntree et al., 2004). Fourthly the interactions were considered self-evident, simple and well-understood. Nevertheless the physical conditions are spatially and temporally variable and different species have different forage demands and foraging behaviours.

BASIC METHODOLOGY

The basic methodology has been published elsewhere (Thornes, 2004). The purpose of this section is to provide briefly a background for the more recent developments described below.

The growth of vegetation on a bare site is assumed to be governed by the logistic equation :

$$dV/dt = rV(1-V/V_{cap}) \qquad \text{Equation 1}$$

in which dV/dt is the rate of growth of vegetation in gm m^{-2} yr^{-1}, V is the vegetation (gm m^{-2}) at the beginning of the growth period. V_{cap} (gm m^{-2}) is the *potential* vegetation that can be reached. It is a function of the available rainfall and evapotranspiration, especially in dry areas where available moisture is limiting. r is the growth coefficient per unit mass of V at low values of V. This equation produces a slow rate of growth at first, the rate of growth increases rapidly; then levels off as V approaches V_{cap}. In a wet year V_{cap} increases and dV/dt goes high. In a dry year V_{cap} decreases and the term in brackets goes negative, so the plants die back towards V_{cap}.

Erosion can similarly be described as logistic. The more erosion there is, the more there will be up to a limit (bare rock!). Here the E_{cap} is the total soil depth. The positive feedback occurs because shallower soils produce more runoff for a given rainfall. Obviously over-shooting cannot occur because erosion is weathering-limited. In other word, the logistic equation only applies to the transport-limited case.

At any time the erosion constrains the plant growth, through lack of moisture storage, and the vegetation constrains the erosion by interception and through increased evapotranspiration.

If equation 1 is expanded and solved for dv/dt = 0, we obtain the equation describing the equilibrium values of vegetation (called the isocline for vegetation, dV/dt = 0). At every point on this isocline the rate of vegetation growth is zero. Similarly the logistic equation for erosion can be solved for dE/dt = 0. When the two are plotted together (Figure 1) the diagram is called the phase space. The intersection of two isoclines is the point where *neither* variable (vegetation or erosion) is changing, as at the point D in Figure 1. At B, vegetation is at a maximum and erosion at zero. At Emax the erosion is at a maximum and vegetation is at zero.

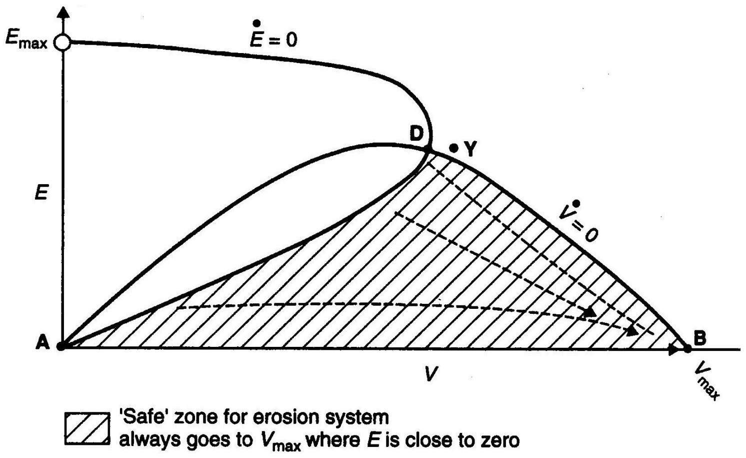

Figure 1 . Phase-space representation of vegetation-erosion interaction (from Thornes, 1985)

At any point in the phase-space diagram, the 'trajectory' of the system can be calculated, describing where the system 'will go' according to the changes given by the two equations. In the shaded area, the dynamics 'take' the system to B, so the triangle ADB is the 'safe zone' for erosion. At D it could go either to B (in the shaded zone) or to Emax (if it is within the dE/dt = 0 curve). The second case is disastrous because it is the 'no vegetation, maximum erosion' solution. Clearly the phase-space representation tells us a great deal about the management options. Thornes (1990) examined these questions with more elaborate systems, including those with stony soils.

To summarise, first obtain the differential equations describing the behaviours of the main variables. Solve them to obtain the isoclines and lastly interpret the phase-space figure to determine the trajectories and stability conditions.

Real Space

The forage varies in geographic space and this has been approached in three ways in the literature:

- By obtaining the variations in biomass from remotely-sensed and mapped data, as in the EU Georange Project. Del Barrio,(personal communication) introduced the idea of 'resistance surfaces-these are maps of the difficulty for grazers to obtain forage.
- Model the spatial variability in forage using a water balance model coupled with topography, aspect and soil characteristics. This approach is being developed in the current EU DeSurvey Project by Thornes and Fonseca.
- Model the spatial variability of biomass according to abstract assumptions. Oksanen (1990) and Thornes, (2004) and have used this approach. Thornes is discussed immediately below and Oksanen in a later section of this paper.

Pursuing the notion of competition between grazers and vegetation and its impact on erosion, Thornes (2004) sought to simulate digitally the emergence of erosional hot spots in adopting the recent paradigm of spatial ecology (Dieckman, Law and Metz, 2000). In this approach the vegetation was initially assumed to be distributed at random over a flat plain and allocated to a cellular framework. In each cell, the vegetation was assumed to increment annually in a logistic fashion, with the V_{cap} set by the annual rainfall. The overall grid was 40 x 40 cells, but results are shown for the innermost 10 x 10 central region (to avoid boundary effects). Grazers are assumed to search at random for forage and their numbers to grow logistically. Their location in the cellular geometry is determined by a cellular-automata model in which a cell is occupied (or not) according to the average amount of biomass in the surrounding cells The cattle disperse from initially random locations according to the cellular automaton rule. Figure 2, for the central region, shows that there is a strong clustering of cattle after only five iterations. The cattle consume forage according to the Nicholson-Bailey (1935) foraging model (cf Regev and Gutierrez below).

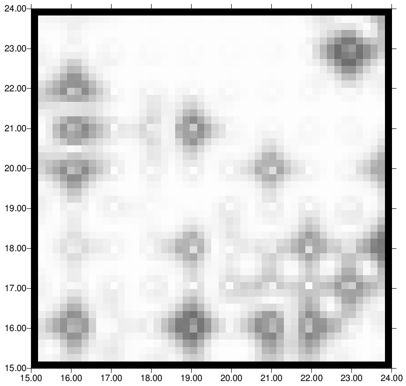

Figure 2. Cattle densities in central region after 5 iterations (from Thornes, 2004)

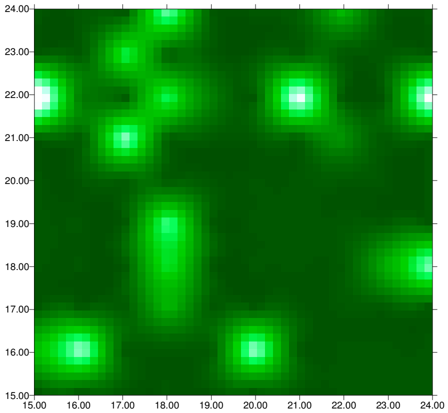

Figure 3. Vegetation density in central region after 10 complete iterations (from Thornes, 2004)

The net result after ten iterations for the central region is shown in Figure 3. The lighter patches are areas of very low or no biomass. They are loci of high potential erosion. This modelling procedure then creates the evolution or *emergence* of a spatial pattern of erosion as a result of the interaction of the resource (mean annual rainfall) with the producer (vegetation) and the predator (grazers) in which the resource is also varying over time.

In this section we have developed the case of competition at a single level of the trophic web. Fretwell (1987) has argued the case for the key role of a three-level trophic web in ecological systems and discussed how new trophic levels could emerge in the vertical hierarchy. Regev et al. (1998) (discussed below) adopted harvesters (human beings) as the highest level.

Spatial exploitation ecosystems

The basic idea of *exploitation* ecosystems is that the dynamic modelling approach described above is combined with spatial variations, allowing dispersal between habitats differing in primary production (vegetation rich and poor regions). This was developed by Oksanen (1990) using the dynamical systems approach.

Essentially Oksanen formulates the differential equations for growth of herbivores and plants. In the herbivore population growth, allowance is made for emigration from the productive areas to the less productive areas, thus shifting the pressure away from the productive areas. The phase-space diagram for this two-level-with-dispersal model is shown in Figure 4. The upwards parabolas to the left are the plant isoclines for productive (upper) and barren (lower) areas. The grazer isoclines are hyperbolic in shape. The vertical dashed line is the plant isocline for both habitats in the absence of grazing. To the left, growth is negative (towards zero) and to the right it is positive. The herbivore isoclines H_a and H_b represent the condition of nearly equal plant productivity (a) and a very barren habitat (b).

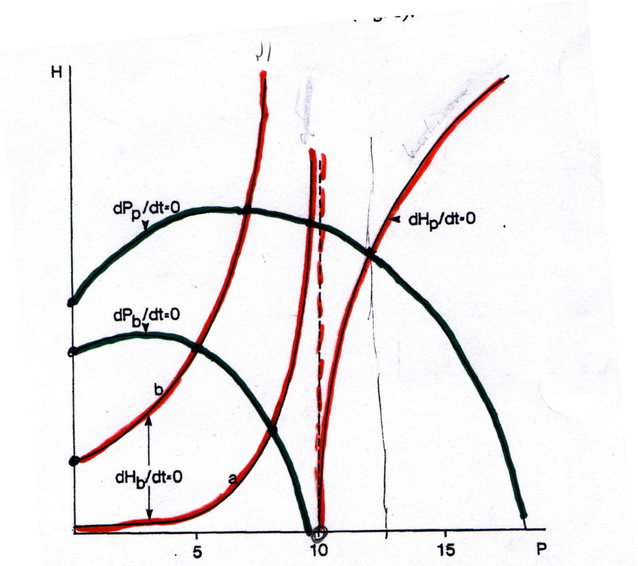

Figure 4. Phase space representation of a two-level, two-zone ecosystem with dispersal (from Oksanen, 1990)

He goes on to analyse the impact of grazing pressure on productivity for the cases (a) and (b). By expressing grazing pressure as the difference between maximum and equilibrium biomass he is able to show that ‘overgrazing’ (ratio >80) is most acute at lower plant productivities and that there is a sharp decrease in ‘overgrazing’ as the productivity rises (as indicated in Figure 5). This decrease is strongest in the barren areas (due to out-migration) and less strong in the more productive areas. This result appears to add strength to the widely-held belief that ‘overgrazing’ (herbivore densities well above equilibrium) is a more serious problem in less productive environments and encourages us to seek the value of plant productivity at which the sharp fall in grazing pressure occurs.

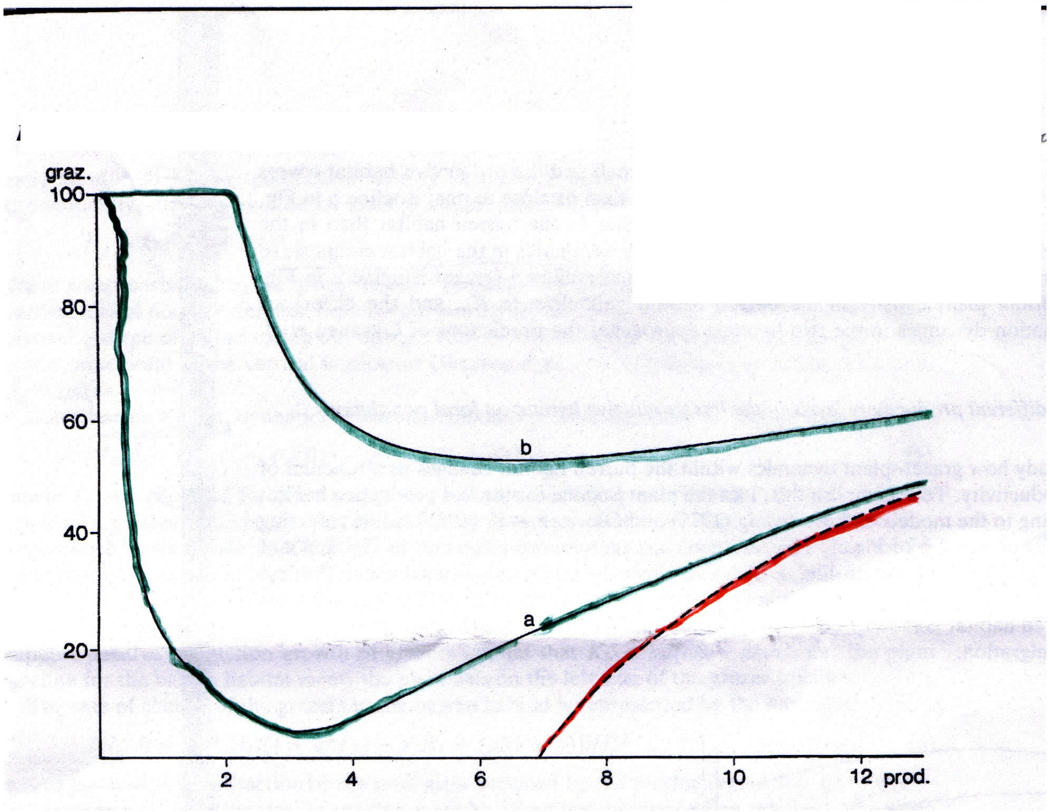

Figure 5. Grazing pressure (overgrazing) plotted against productivity for the two-level, two-zone model of Oksanen (from Oksanen, 1990)

Towards a general trophic model

The results obtained by this overall methodology of investigating the dynamic behaviour of trophic-web systems rest heavily on the choice of the governing differential equations. In the model developed by Thornes (2004) and described above for the emergence of erosion ‘hot spots’, the assumption was made that the consumption by grazing animals of the plant biomass resulted from a random search. Here the prey (grazers) encounter the forage (palatable biomass) at random, but in a function that is related to the prey density and the effective area of search by the prey. The equations used in the Oksanen model also relate more formally to the search efficiency and the time spent ‘handling’ the prey. These parameters also appear in the isoclines and determine the graphic interpretation of the behaviour.

Gutierrez (1992) has moved on to a more general model of exploitation in a trophic-web system, involving three (or n) levels, the lowest of which is a resource above which is a producer and one or more predator levels. Assuming the representation R x y, R is the base resource harvested by x and x is harvested by y. In other words, the competition is vertical as well as horizontal (same species, one trophic level as in the model and methodology described above). To apply the theory to land degradation, the basic resource is rainfall in semi-arid environments. The second level consists of plants that prey on the water supply for their growth. The third level comprises the herbivores that consume the plants. Above this (and considered below) are the human harvesters that feed on the herbivores. The top predators are constrained by economic considerations such as profit maximisation. These effects ripple up and down the chain. For land degradation, the link is between erosion and vegetation and the impact of the herbivores from above and variations of the water balance from below on the plant canopy. As these two 'squeezes' vary, so does the erosion rate, especially if the system is close to a critical isocline

Another important aspect of Gutierrez's work is that the demand made by level i (e.g. herbivores) on the level i-1 (e.g. plants) is not simply dependent on the population of level i-1 or its biomass, but also on the ratio of the supply at level i to the demand at i-1. Gutierrez's fundamental equation is:

$$dM_i/dt = \theta_i M_i D_i h(\mu_i) - \nu_i(D_i) M_i - M_{i+1} D_{i+1} h(\mu_{i+1}) \qquad \text{Equation 2}$$

This makes the growth in mass in time t at level i (say of herbivores at time t) a function of the mass of herbivores, multiplied by a resource acquisition function h(μ) which itself is a negative exponential function of the supply from the next level down to the demand for the present level (e.g. the supply of forage to the demand for forage). This has the advantage of supplying an appropriate economic analogy for the highest level, which is human harvesting (Regev et al., 1998; Gutierrez and Regev, 2004).

Ecological economics and the vegetation-erosion interaction

The work of Regev and Gutierrez is important in combining ecological and economic constraints on resource use, an approach that they call ecological economics. This approach is based on dynamical modelling of trophic web behaviour using the methodology sketched above. Using a trophic web with several levels, they adopt both 'horizontal' and 'vertical' predation as constraints on an economic objective function. The economic objective function is the mathematical expression of the hoped-for goal (e.g. maximum profit).

The governing differential equations are based on the equation described in the last section (Equation 2), i.e. on the mass change at a given trophic level as a function of the population (mass) at that level and the demand from the level above. These are solved for optimisation of two cases: (i) competing for individual profits gained from the consumption stream and (ii) the present value of benefit integrated over an infinite time horizon (sustainable gains). These maximisations are obtained subject to the constraints of the governing differential equations for behaviour – a non-trivial mathematical exercise using the Hamiltonian procedure, as outlined in Regev et al. (1998).

These arguments produce the phase-space representations shown in Figure 6. Here the gain (λ_1) is shown in relation to resource density (x) at the lowest level. The left hand graph shows the isoclines for gains ($d\lambda/dt=0$) and for the resource ($dx/dt=0$). The right-angled arrows show the direction of trajectories about the mutual equilibrium point for which x_s is the resource value (in our case, x_s is the stable plant biomass in the presence of grazing animals that are producing a marginal gain λ_1).

In Gutierrez and Regev (2004), the problem is a two-level trophic web for the two optimisations (individual profit and societal gains). Their overall results in phase-space are shown in Figure 7.

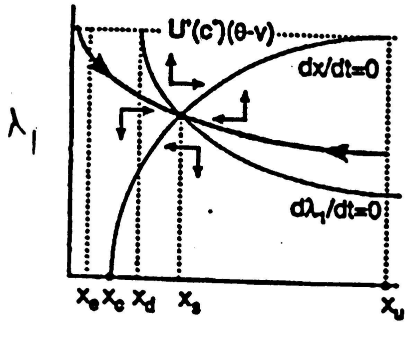

Figure 6. Phase-space representation of ecological-economic model of Regev-Gutierrez (Regev-Gutierrez, 2004)

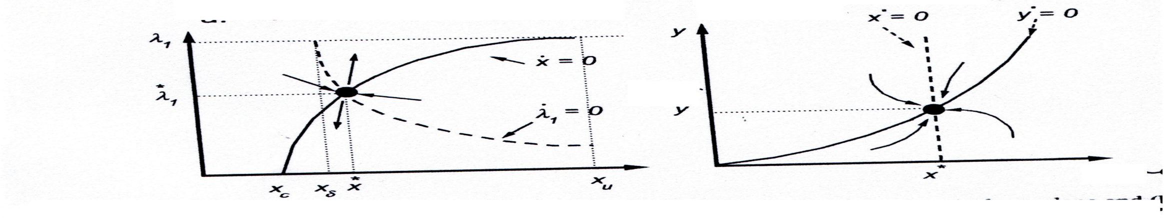

Figure 7 Phase-space representation of the simplified Regev-Gutierrez model
(FromRegev-Gutierrez,2004)

In the left figure (free market) gain ($\lambda_{1)}$ is plotted against resource (x) and the corresponding isoclines for Dx/dt=0 and dλ_1/dt=0 are given. The joint equilibrium is unstable. Because the trajectories move away from the equilibrium a slight perturbation will drive the system towards an upper limit of $\lambda_{1,}$ or towards $\lambda_{1=0.}$ By contrast, the societal objective function analysis, depicted in the right-hand graph, shows a stable equilibrium at x* and y*. In both their papers, Regev and Gutierrez go on to consider the sensitivity of these solutions to variations of the parameters of the governing equations.

Our interest here lies in the right-hand case, with vegetation as the resource and herbivores as the predators. We are especially interested in obtaining (i) the stable equilibrium point that leaves our vegetation fixed and (ii) the herbivore density (y) that will yield this stable equilibrium under a societal utility function. These would produce the optimum sustainable plant cover above a critical level.

Gutierrez and Regev (2004) also examine the effect of changing the base resource (x) downwards. The result implies no change in the marginal gain, but the equilibrium point is shifted to lower values of x beyond the level of extinction. That is, the individual profit margin will remain constant, but the resource base will move into the ‘extinction’ zone.

Summary – towards a theory of vegetation-erosion interactions

This review has outlined developments in exploitation ecology and in ecological economics that appear to offer possibilities of progression towards the problem of vegetation-erosion-grazing interactions that are central to the theoretical solution of the grazing desertification syndrome.

The continued use of the mantra of over-grazing as a cause of catastrophic erosion is based on the observation that, as vegetation falls below about 30%, then catastrophic erosion ensues. Moreover, in water-limited biospheres, it is found that this canopy cover occurs when the ratio of actual to potential evapotranspiration is about one third. In addition, the ratio of herbivore density to equilibrium herbivore density for a given vegetation cover (a definition of over-grazing) increases dramatically when free migration of herbivores is allowed in marginal patchy productivity in the vegetation biomass. Moreover, the dynamical behaviour under conditions of free-range grazing gives rise to the emergence of erosional hot-spots without the need for special pleading (piosphere effect or 'standing areas' at grazing stations).

Above all this, the development of dynamical models that link ecology and economics could provide a mechanism for establishing the stability and sustainability of ecologically sound erosion management schemes based on changing resource density in a time of climatic change.

Two major obstacles in this theory are the assumption of free-range herding and economic discount rates. Free-range herding implies that herbivores act in an open competition in a free market sense. In the Mediterranean and many other areas of the world, the animals are managed by shepherds who hopefully act in a Darwinian sense, foreseeing that their survival depends on careful management of the basic resource. The above arguments take this into account only in the sense of the societal optimisation of Gutierrez and Regev (2004). Thus there is scope for the modelling of 'Darwinian shepherds' with a mixture of well-informed learning behaviour and altruistic sustainable motivation. The discount rates are more usually considered to be controlled at the macro-economic level and hence are beyond the control of local managers.

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